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Flux Profiles in the Marine Layer Over the Open Ocean

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The research conducted under this grant was a part of the Marine Boundary Layers (MBL) ONR Accelerated Research Initiative. The UCI portion was to prepare and execute an experiment based on the stable Research Platform FLIP to measure the wind, wave and turbulence structure in the atmospheric surface layer over open ocean waves. We collaborated with Dr. Jim Edson of Woods Hole Institution of Oceanography (WHOI) and others in the second of the MBL FLIP experiments, MBL II.

The specific purpose of the research is to make accurate, precise measurements of the wind profile, wind stress, pressure, and surface waves to determine if previous results obtained primarily from over-land surface-layer experiments hold over the sea. Previous attempts to measure the wind profile over the ocean, in other than very shallow water, were compromised by instrumentation problems and other factors.

Several theoretical and modeling analyses of the flow over waves were untested against experimental data, which also motivated the our study. The main framework for the analysis of the atmospheric surface layer has been Monin-Obukhov similarity theory, which describes the constant flux surface layer in terms of modification of the semi-logarithmic "Law-of-the-Wall" by buoyant stability. This concept was largely verified by the 1968 Kansas experiment, which also determined many empirical constants. However, Monin-Obuhkov similarity theory does not address the many possible effects of waves on the profiles and surface-layer turbulence; i.e., it has not been completely tested over the ocean.

For MBL II, we at UCI designed and prepared instrumentation for the measurement of:

- Wind Profile. 12 fast-response cup and vane anemometers.
- Wind Stress. 5, 3-dimensional sonic anemometers. (With Dr. Jim Edson of WHOI.)
- Fluctuation Pressure. 3 NOAA ETL pressure sensors. (With Dr. Jim Wilczak.)
- Surface Wave and Slope. 4 wave wires. (With Lloyd Green of Scripps.)

- FLIP Mast. Design and fabrication of 15 meter mast for the profile instrumentation.
- Motion. Select and deploy instrumentation to monitor the residual motion of FLIP and the mast.
- Data System. Assembly and design of software for a data system to acquire 80 channels of data at 50 Hz sample rate continuously without gaps for the experiment.

The instrumentation program occurred from July 1, 1993 to September 1, 1994 and resulted in a successful trial 7-day cruise on FLIP off San Diego in September 1994. In particular, the deployment of the mast from the end of FLIP's port boom was successful, and the data system software worked well.

More levels of wind speed and direction were added for the main cruise of MBL II.

For MBL II, groups from University of Massachusetts, New Zealand, Scripps Institution of Oceanography, WHOI Chemical Oceanography and Ocean Engineering, and UCI joined for a 25-day cruise on FLIP. After repairs were made of some damage at sea during the tow from San Diego, FLIP was successfully moored in about 1 km of water 30km off of Pt. Sur, CA. This was the first 3-point moor of FLIP at a specified heading, which was chosen to minimize flow distortion at the mast due to FLIP's hull.

R/V Oceanus, R/V New Horizon and R/V Pt. Sur participated in MBL II, as well as the Long-Ez aircraft from NOAA Oak Ridge.

MBL II was a successful experiment. Practically all systems on all platforms worked well. Data quality was high.

For the UCI portion of MBL II (with Dr. Jim Edson of WHOI), we obtained some 7 gigabytes of data over 14 days with very few problems in data gaps or quality. Equally as important, we had very good and interesting wind/wave conditions. At the start of the data-acquisition period, the winds and wave directions were opposite. This was followed by a short transition period of slack winds and waves to the normal spring-time conditions of building down-coast winds (from the northwest), culminating in close to 20 meter per second (40 knot) winds and a fairly high sea-state. (The two cup anemometer levels nearest the ocean were damaged by the high waves at this time.) After the peak winds, they decreased but with a fairly large swell running. Thus the MBL II data set covers a wide and interesting range of wind and wave conditions.

Since the completion of the MBL II experimental phase in May 1994, effort has concentrated on the analysis of the massive 7 GB data set. We have developed software for accessing processing the data, including spectral and cross-spectral analysis.

Results to date are the following:

- Wind Profile. The wind profile is modulated by the surface waves up to at least 18 meters above the sea. The profile appears to follow the semi-logarithmic 'Law-of-the-Wall' from above about 10 meters above the sea, with substantial deviations below

that level. The effect of surface waves, in terms of apparent roughness, is to follow Charnock's relation above 10 meters, and an aerodynamically smooth wall below but with a von Karman constant considerably larger than that over land.

- Phase Characteristics. With a newly-developed Hilbert transform technique by Dr. Tihomir Hristov of UCI, we have been able to elucidate the wave-induced features of any signal (wind, turbulence, pressure, etc.) with respect to the average wave shape over a data time interval long enough to average-out turbulent noise. This new technique applies to non-monochromatic waves, and solves a long-standing problem in wind-wave interaction. For the first time, we can clearly extract the wave-coherent features of the flow.

- Wind Stress. The key tenet of Monin-Obuhkov surface-layer similarity theory is that the vertical flux of horizontal momentum (turbulent wind stress) is constant with height. With the experimental design in MBL II, we were able to examine this key assumption. Generally it holds, although there are periods where it does not and stress divergence is large. This appears to depend on slight mis-alignment of wind and wave directions.

- Drag Coefficient. A bottom-line result from air-sea interaction experiments is the parameterization of wind stress in terms of the drag coefficient - the fraction of mean horizontal momentum in the wind that is transferred to the underlying sea surface. The results from MBL II give general agreement with those of previous studies, and it appears that some of ubiquitous scatter in drag coefficient-wind speed correlations may be due to the aforementioned stress divergence. When it is large, the drag coefficient is increased by up to 40%.

- Motion Corrections. While FLIP is an excellent stable platform, there are some residual motions, particularly at the mast where the flexibility of the long port boom is a factor. We have, with Dr. Jim Edson of WHOI, developed procedures to correct the wind and wind stress results for the slight pitching, rolling, yawing and heaving motions of the sensors. This is particularly important since we are looking for wave-coherent effects, and it is the waves that are causing the motion. Our methods appear to remove the motion contamination well.

- Pressure Fluctuations. Our preliminary analysis of the fluctuating pressure signals indicate that at least one of the three sensors was operating properly, and that the phase-induced pressure signal relative to the wave height clearly shows periods of wave growth and retardation due to pressure forces on the waves.

The following were presentations made during the grant period:

- Organizational meeting for MBL II, held in San Francisco in December of 1994. There, all investigators assembled and planned the experimental details for MBL II. The meeting was organized and run by C A Friehe of UCI.

- After MBL II, a meeting of MBL investigators was held in August of 1995 at UCI to present and review initial results from MBL I and II. The meeting was organized and run by C A Friehe of UCI.

- A special session of the 1996 AGU/ASLO Ocean Sciences meeting on MBL was proposed by C A Friehe and Jim Edson and accepted. Our papers presented there were:

- Miller, S., Friehe, C., Hristov, T. and J. Edson, "Wind Profile and Turbulence Over Ocean Waves, " *EOS Trans. AGU*, **77**, no. 3, Ocean Sciences Meeting Suppl., OS108, 1996.

- Wetzel, S. W., Edson, J. B., Miller, S. D. and C. A. Friehe, "Phase Averaging of Open Ocean Wave and Wind Fields," *Eos Trans. AGU*, **77**, no. 3, Ocean Sciences Meeting Suppl., OS108, 1996.

- Hristov, T., Friehe, C., Miller, S. D. and J. Edson, "Wind, Wind Stress and Wave Spectra from the MBL II Experiment," *Eos Trans. AGU*, **77**, no. 3, Ocean Sciences Meeting Suppl., OS141, 1996.

We also participated in the Air-Sea Gas meeting organized by Prof. Bernd Jahne and the American Physical Society Division of Fluid Dynamics:

- Miller, S., Friehe, C. A., Hristov, T. and J. Edson, "Wind and Stress Profiles over Ocean Waves," Third International Symposium on Air-Water Gas Transfer, Heidelberg, Germany, 1995.

- Friehe, C. A. and P. Fuehrer, "A Space-Time Scale Analysis of Atmospheric Turbulence," American Physical Society, Division of Fluid Dynamics, Atlanta, GA 1994.

- Miller, S. D., C. A. Friehe, T. Hristov and J. B. Edson, "Wind Profile and Turbulence over Ocean Waves," American Physical Society, Division of Fluid Dynamics, (*Bulletin APS*, **40**, no. 12, p. 1971), November 1995.

- Fuehrer, P. L. and C. A. Friehe, "A Turbulence Model for Signal Decomposition of Velocity Time Series," American Physical Society, Division of Fluid Dynamics, (*Bulletin APS*, **40**, no. 12, p. 1931), November 1995.